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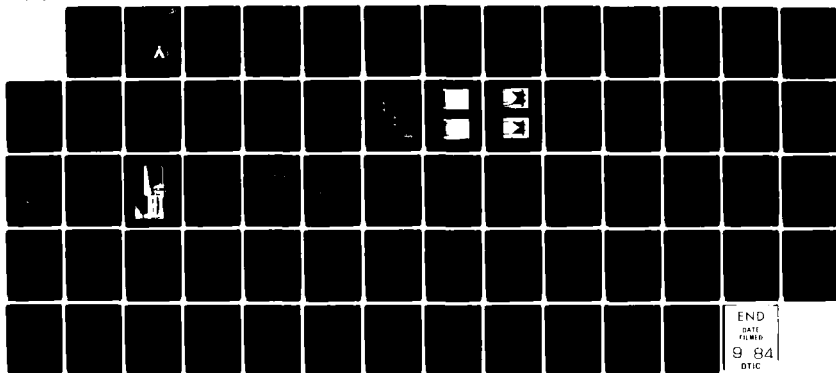
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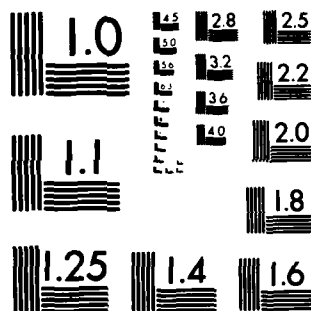
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PRELIMINARY DESIGN OF A
REUSEABLE PPMHD POWER SUPPLY
TEST BED FACILITY

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S.P. Gill, W.L. Shimmin, J.D. Watson

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SUMMARY

This report describes a preliminary design of a reusable pulsed plasma MHD (PPMHD) power supply test bed facility that operates in the gigawatt/megajoule regime. The resulting design can be sized to provide output pulse energies suitable for a range of advanced applications.

The report includes a summary of the experimental performance data base for PPMHD. This is followed by a discussion of computed power supply performance sensitivity to resistive and inductive loads. The current status of PPMHD component technologies is described as a basis for present and future hardware designs. This includes a discussion of an approach to self-excited operation which is an extension of demonstrated component technologies.

Size scaling relations are presented for estimating PPMHD power supply weights in terms of electrical output power and energy. Two power supply configurations are described. The first is a state-of-the-art power supply that would be used as an experimental test bed for component development. This device would initially output a 65 kJ pulse at 2 GW and would be upgraded over a four year period to output nearly 500 kJ at 13 GW. The second example is a large device with a 5 megajoule output incorporating many projected engineering advances in component design. The reusable 5 MJ power supply, which includes full containment of the explosive cartridge, self-excited generator, auxiliary power supply, and output impedance transformer, is projected to weigh 3000 kg. This design would be suitable for advanced EM launcher test bed development programs.

A four year test bed development program is outlined. The program is organized around a small, reusable PPMHD test bed whose components can be evaluated and progressively upgraded at relatively low cost. The goal of this program is to develop an efficient PPMHD power supply requiring minimal auxiliary operating power. The design will be capable of rep-rated operation with the addition of an autoloader mechanism.

1.0 INTRODUCTION

The objective of this program is to develop a preliminary design of a reuseable pulsed plasma MHD (PPMHD) power supply test bed facility that operates in the gigawatt/megajoule regime. The resulting design can be sized to provide output pulse energies suitable for a range of advanced applications.

The report includes a summary of the experimental performance data base for PPMHD. This is followed by a discussion of computed power supply performance sensitivity to resistive and inductive loads. The current status of PPMHD component technologies is described as a basis for present and future hardware designs. This includes a discussion of an approach to self-excited operation which is an extension of demonstrated component technologies.

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A four year experimental development program is outlined. The program is organized around a small, reuseable PPMHD test bed whose components can be evaluated and progressively upgraded at relatively low cost. The goal of this program is to develop an efficient PPMHD power supply requiring minimal auxiliary operating power. The design will be capable of rep-rated operation with the addition of an autoloader mechanism.

1.1 Pulsed Plasma MHD Overview

The Artec PPMHD power supply concept is distinguished by being a lightweight, compact ordnance device. It shares the virtues of gun systems in terms of instant start-up, reliability, and long shelf life of the cartridges. The components are rugged and compatible with existing military logistics. The PPMHD generator has a unique role in military applications because of this ordnance character. The generator is a prime power source for pulsed electrical energy, requiring minimal auxiliary equipment to operate,

and can deliver full power to the load within a few hundred microseconds of initiation. The peak power/pulse energy performance envelope characteristic of PPMHD power supplies is shown in Figure 1.

The primary energy store in pulsed plasma MHD is an expendable cartridge which contains the explosive charge and working gas. When initiated, the cartridge delivers a pulse of energetic plasma to a fixed Faraday mode generator in which the plasma is the only moving part. Here plasma flow energy is converted to electrical energy. This sequence can be automated for repetitive pulsing by cycling cartridges with an autoloader mechanism based on established ordnance practice. The basic innovation of the PPMHD generator is the efficient conversion of chemical energy of explosives to electrical energy at gigawatt power levels by a compact ordnance-like device.

From a scientific point of view, pulsed plasma MHD is a transient MHD process based on a Faraday mode generator. The dense non-ideal plasma flow is characterized by flow velocities of 10 to 30 km/s and electrical conductivities of 15 to 40 kS/m. Another distinguishing feature is the high magnetic Reynolds number at which the PPMHD generator is operated. Experiments have been conducted at magnetic Reynolds numbers of up to 35.

In the most recent experiment (Reference 1), a 500 kJ, 80 microsecond electrical pulse was delivered to a resistive load at a peak power of 10.5 GW.

The PPMHD generator is a prime power source with a high current output and therefore can be considered an excellent magnetic flux generator. On the other hand, a device such as the magneto-cumulative generator (MCG) or flux compressor is not a true prime power source since it must be provided with a priming flux. It is more properly a magnetic flux compressor. The combination of an MCG with a small PPMHD generator to provide the priming flux would form an extremely lightweight, single shot power supply.

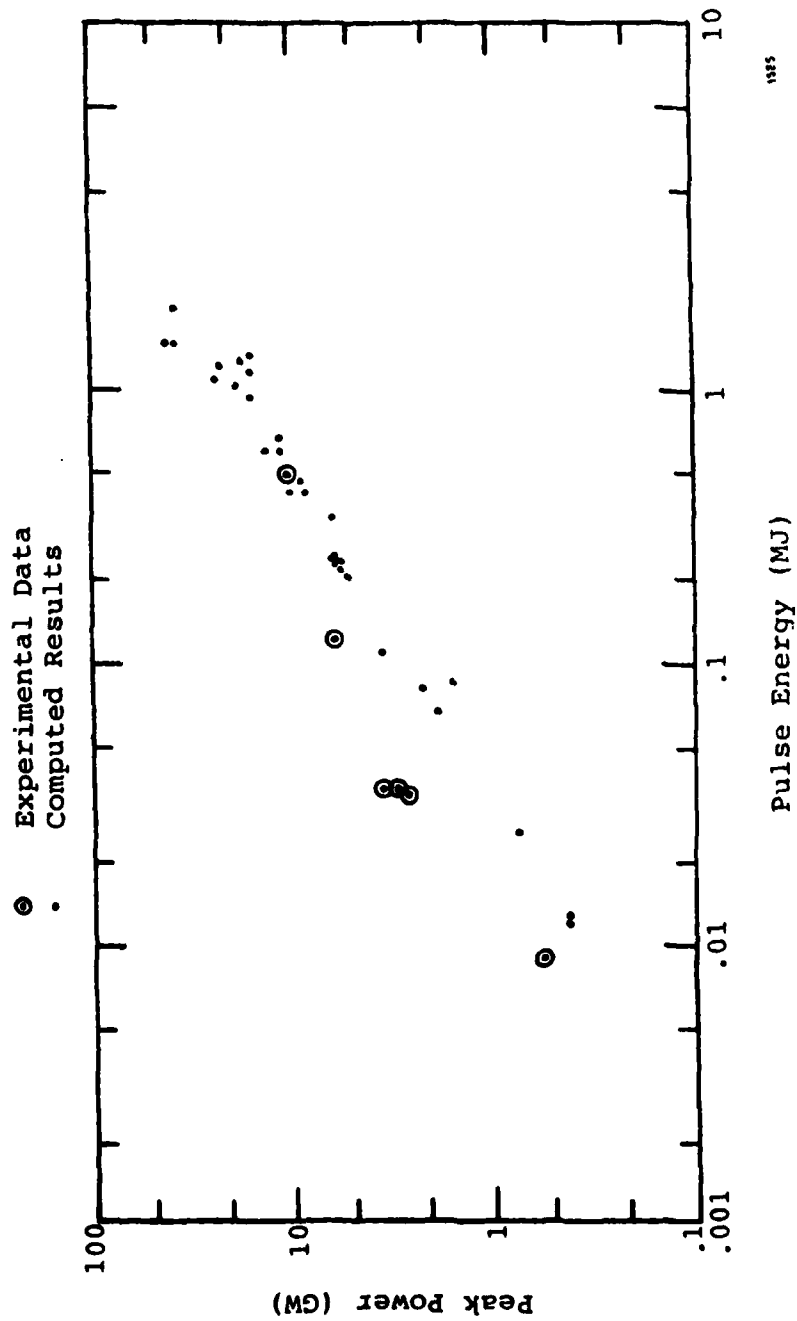


Figure 1 PPMHD Power-Energy Regime

2.0 PERFORMANCE DATA BASE

2.1 Experimental Data Base

Several PPMHD experiments in which peak powers greater than 1 GW form the experimental data base used in the estimates and analysis of Section 3.0. These experiments are summarized in Table 1 and are fully described in References 1 and 2. As discussed in Reference 1, several of the experiments exhibited premature shorting of the generator and full energy was not delivered to the load. For example, in the 165-9 experiment, the measured energy delivered to the load was 500 kJ. The matching calculation of output indicated that the design was capable of generating over 800 kJ. This is considered to be the expected output for the parameters of the 165-9 design.

2.2 Computed Sensitivity to External Loads

A computer simulation code for the PPMHD process has been developed and is also reported in Reference 1. The code models the PPMHD process from the generation of the plasma through the interaction of the flow with the Faraday generator and external circuit (Figure 2). As discussed in Reference 1 the code has been calibrated to the available data base principally by modeling the details of the plasma source operation to yield the observed electrical output.

The simulation code has become an important design tool because of the strong interaction between the plasma flow and the external circuit. In addition to providing detailed distribution of energy in the system, the code has been used to evaluate the output of the PPMHD generator under different load impedance conditions. Computed peak power/pulse energy results are included in Figure 1 along with the experimental data to illustrate the output states possible with different generator and load parameters.

In general, the output of a PPMHD generator must be transformed to match the load. For most purposes, a first stage impedance transformation is made within the MHD channel assembly to minimize resistive losses and control magnetic forces associated with the megampere output currents from the Faraday generator electrodes. This transformer must match load impedance to near the optimum impedance required by the Faraday generator to achieve efficient energy transfer.

Experiment	No. of Electrode Pairs	Channel Diameter (mm)	B-Field (T)	Electrode Area (mm ²)	Peak Power (GW)	Energy to Load (kJ)
165-3	4	25.4	2.1	2000	0.56	9 in 25 μ s
165-4	2	25.4	5.2	2000	3.42	37 in 23 μ s
165-5	1	25.4	5.2	2400	2.97	37 in 22 μ s
165-6	1	25.4	4.7	2400	2.55	35 in 22 μ s
165-7	1	38.1	5.6	4800	6.27	126 in 40 μ s
165-9	2	50.8	5.27	24576	10.45	502 in 95 μ s

TABLE 1 Summary of High Power MHD Experiments

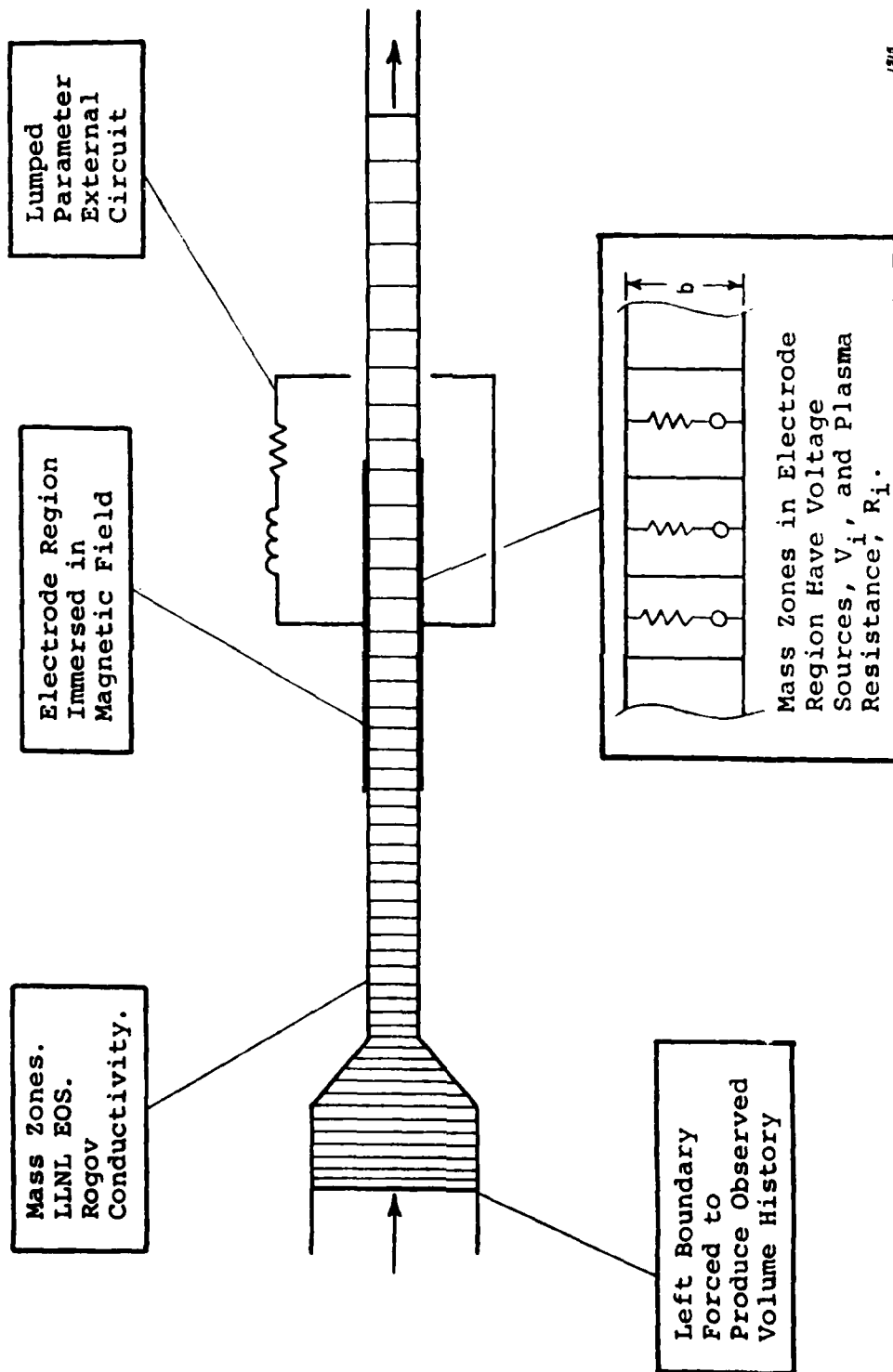


Figure 2 PPMHD Finite Difference Simulation Code

Calculations of peak power and energy into both pure resistive and pure inductive loads have been made to illustrate the sensitivity of the PPMHD generator to load impedance. A 50.8 mm diameter MHD channel with .65m long electrodes and an applied B-field of 6 tesla were chosen as a reference. These parameters are close to those of our most recent experiment (Shot 165-9). In these calculations, two plasma source models were used. The first is representative of our current level of technology and the second assumes plasma source development for improved performance.

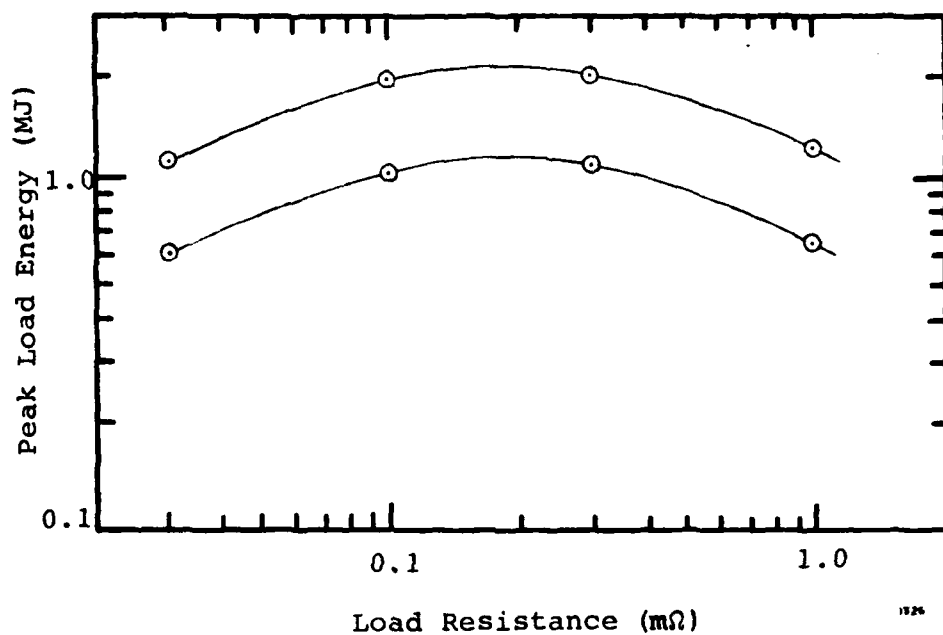
The results of these calculations are shown in Figures 3 and 4. Maximum energy is delivered to a purely resistive load of about 0.2 milliohms and a purely inductive load of about 10 nanohenries. The average plasma resistance and interelectrode inductance are about 0.1 milliohms and 0.9 nanohenries respectively. Output is relatively insensitive to load impedance because of the capacity of the MHD process to adjust when long electrodes are used. At conditions of optimum energy transfer, the energy delivered to the purely inductive load is just over 80% of that delivered to the purely resistive load. For both plasma sources the highest output energies represent a 30% conversion of plasma flow energy to electrical.

2.3 PPMHD Efficiency

The important energy conversion processes in PPMHD are:

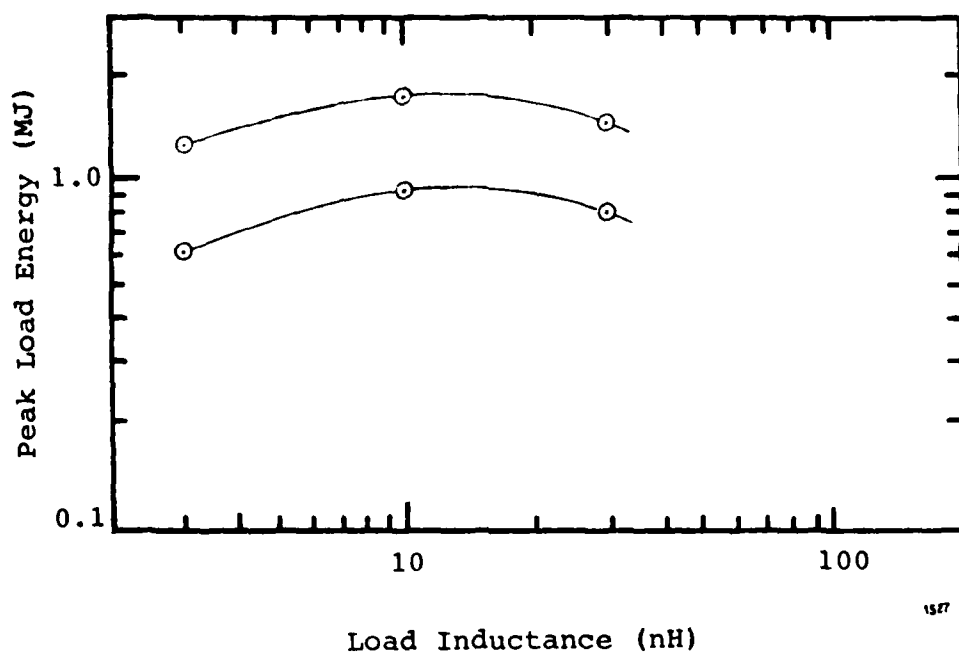
1. Chemical energy of an explosive is converted to plasma energy in the plasma source cartridge.
2. The plasma is driven into an MHD channel, converting plasma internal energy to kinetic energy.
3. The flowing plasma passes through a Faraday mode MHD generator in the MHD channel where electrical energy is extracted from the flow.

A magnetic field is established across the MHD channel by an external source of electrical energy. The energy required for the magnetic field is expressed in terms of the output electrical energy of the PPMHD generator by an amplification factor.



Applied Magnetic Field	6T
Electrode Length	.65 meters
MHD Channel Diameter	.0508 meters

Figure 3 Computed Energy Delivered to Pure Resistive Loads by a PPMHD Generator



Applied Magnetic Field	6T
Electrode Length	.65 meters
MHD Channel Diameter	.0508 meters

Figure 4 Computed Energy Delivered to Pure Inductive Loads by a PPMHD Generator

As discussed in Reference 1, the process conversion efficiencies and field amplification representative of the current state of PPMHD technology are:

* Explosive energy to plasma energy in the plasma source cartridge	9%
* Plasma energy in the cartridge to plasma energy past the MHD generator	81%
* Plasma energy past the generator to electrical energy in the load	27%
* Amplification factor - electrical energy in the load to applied field energy	6.2

PPMHD conversion efficiency is defined as the electrical energy delivered to the load as a percentage of the chemical energy of the explosive. For the parameters of the 165-9 experiment the conversion efficiency is 2%. The energy required to establish the magnetic field is 16% of the PPMHD electrical output energy.

Reasonable estimates for process conversion efficiencies and field amplification for projected PPMHD technology are:

* Explosive energy to plasma energy in the plasma source cartridge	30%
* Plasma energy in the cartridge to plasma energy past the MHD generator	80%
* Plasma energy past the generator to electrical energy in the load	50%
* Amplification factor - electrical energy in the load to applied field energy	40

Projected PPMHD conversion efficiency is estimated to be 12%. The bases for these projections are discussed in Section 3.0. The energy required to establish the magnetic field is estimated to be 2.5% of the PPMHD electrical output energy based on a self-excited mode of generator operation discussed in Subsection 3.3.4.

3.0 PPMHD COMPONENT TECHNOLOGY

3.1 Plasma Source Cartridge

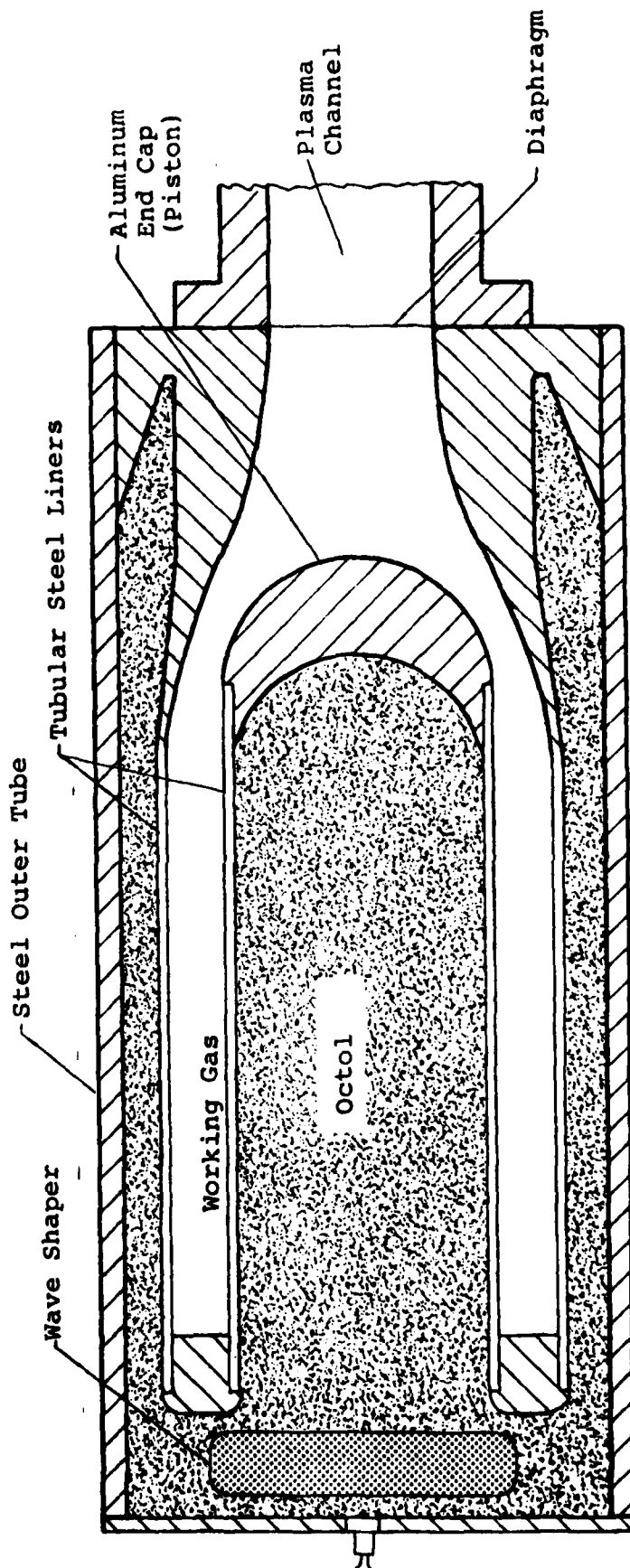
The chemical energy of an explosive is converted to plasma energy in the plasma source shown schematically in Figure 5. Octol explosive is cast around a steel lined annular region containing the pressurized working gas. By means of a wave shaper the detonation front is caused to pass simultaneously along the outer and inner liners progressively collapsing the annular volume. The impact of the liners forms a dynamic seal which moves at the explosive detonation velocity and drives a strong, high pressure shock into the working gas.

The plasma forced to flow at the detonation velocity of the explosive converges into the end cavity and is further energized by an aluminum piston driven by the inner cylinder of explosive. The piston continues collapsing the cavity volume driving the plasma into the MHD channel. The sequential operation of the plasma source is illustrated schematically in Figure 6. The operation of the plasma source has been experimentally verified in a series of 120 MeV radiographs (Figures 7 and 8).

The specific energy of Octol explosive is 5.3 MJ/kg. The energized working gas or plasma driven down the MHD channel has an estimated average specific energy of 70 MJ/kg. The increase in specific energy results from efficiently converting energy from a mass of explosive to a much smaller mass of plasma.

In the operation of the plasma source, the dynamic gas seal formed by the colliding metal shells is critical. As discussed in Reference 1, we have estimated that approximately 40% of the plasma is overrun in the region of the seal and lost to the system in the present design. Thus the characteristic pressures in the shocked plasma are on the order of 18×10^8 Pa (18 kbar) instead of the 30×10^8 Pa which was the original design intent. From Figure 6, it is seen that not all of the gas is directly processed by the colliding shells. In the design used in the 165-9 experiment, .082 kg of gas was initially loaded into the cartridge. Of this, .056 kg of gas was energized and driven into the MHD channel. The other .026 kg was overrun by the colliding shells and lost. These estimates have been made using our simulation code by matching the computed performance to the observed performance as discussed in Reference 1.

We believe that, with a redesign of the start-up process whereby the dynamic seal is initially formed, the loss of plasma can be substantially reduced. This is a key



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Figure 5 Schematic of Explosively Driven Plasma Source

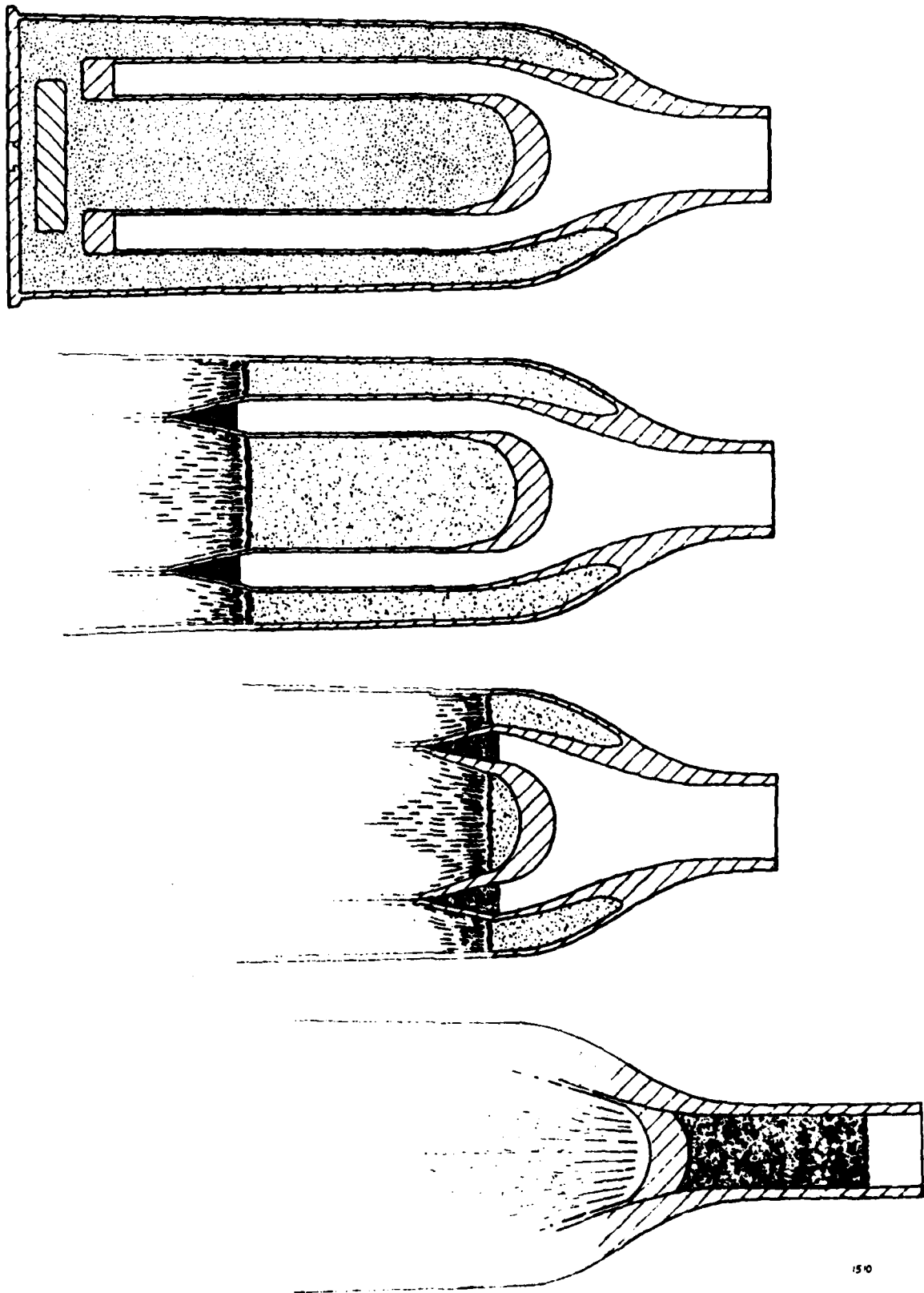
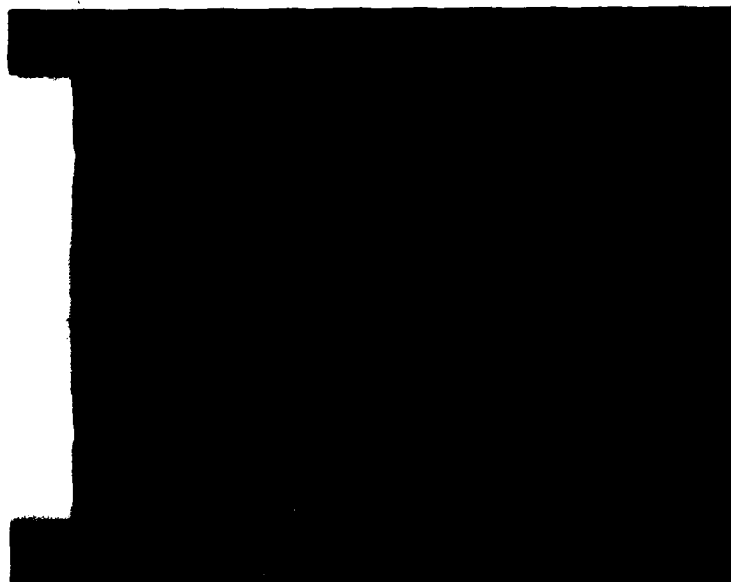


Figure 6 Sequence of Plasma Source Operation

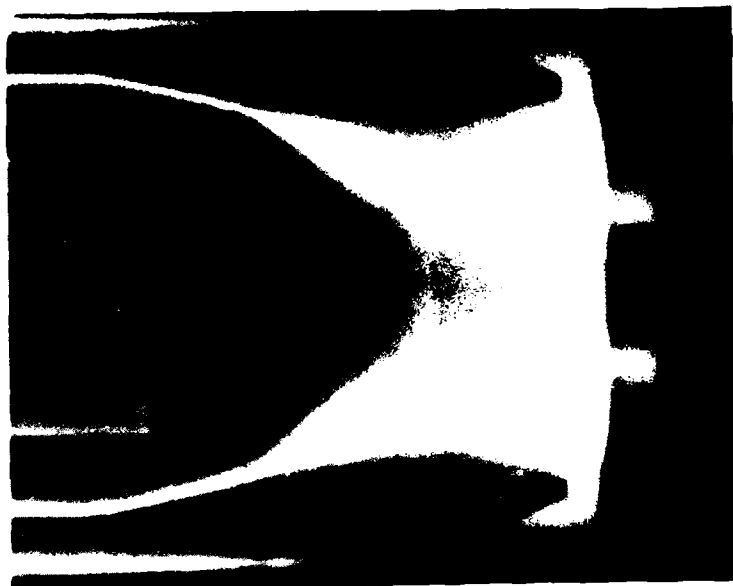


a) Plasma Source Back End Before Firing

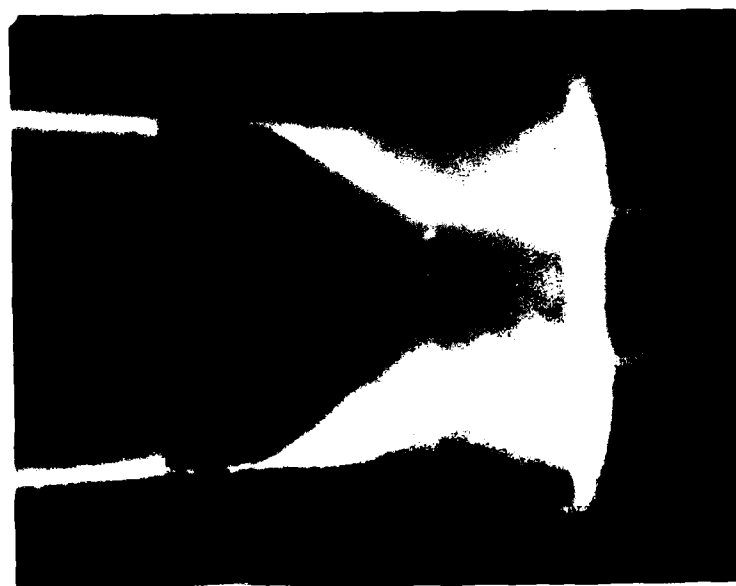


b) Plasma Source Back End During Operation

Figure 7 Flash X-Ray of Plasma Source



a) Plasma Source Front End Before Firing



b) Plasma Source Front End During Operation

Figure 8 Flash X-Ray of Plasma Source

technical issue involved in plasma source design. Large performance gains can be made here as no attempt has yet been made to optimize either the start-up process or the overall design parameters of the plasma source. Ultimately we estimate that 30 to 40x10⁸ Pa pressures can be contained by proper design of the start-up process. This and other engineering modifications to the present design should lead to overall energy conversion efficiencies in the plasma source of 25 to 30% (chemical energy of explosive to kinetic and internal energy of the plasma).

The plasma source cartridge used in previous experiments and shown in Figure 5 has a thick-wall outer steel case to provide inertial confinement of the explosive products behind the detonation front. This outer steel case is a source of shrapnel that can be very damaging if allowed to accelerate. In breech assembly designs discussed in the next section, the outer steel case is discarded and a standoff gap is placed between the outer layer of explosive and the inner wall of the breech assembly containment vessel. To maintain the same impulse or pressure history on the collapsing steel liners of the plasma source, the thickness of the outer layer of explosive must be increased to compensate for the removal of the steel case. A number of 1-D cylindrical finite difference calculations were made to size the required layer of explosive. This type of calculation and the experimental basis for it are described fully in Reference 3.

These calculations have shown that the operation of the plasma source would be unaffected by removing the outer steel case and increasing the outer explosive layer by 50%. This will decrease the weight of the plasma source cartridge but will also decrease the conversion efficiency of explosive energy to plasma energy.

3.2 Breech Assembly

Up to this time all PPMHD experiments have been carried out with uncontained plasma sources to permit flash X-ray coverage of the internal source operation. Until recently, we have not attempted containment of the plasma source cartridge. Preliminary experiments to demonstrate containment are discussed in Subsection 3.2.4.

Ultimately a rep-rated PPMHD power supply will be operated like a rapid fire gun, inserting the cartridge, firing, and extracting the spent cartridge. This will be a difficult engineering challenge primarily due to the complications of dealing with the very high but short-lived detonation pressures and with the potential problems of round extraction. Containment of both large and small explosive

charges has been demonstrated by many workers in single shot mode but to our knowledge never in rapid-fire mode.

3.2.1 Mitigation by Alternating Material Layers

During this program, we evaluated two methods of cartridge containment. In the first, the space between the outer layer of cartridge explosive and the inner wall of the containment vessel is filled by a mitigation system comprised of several layers of material of alternating shock impedance. The function of this mitigation system is to attenuate the peak transmitted pressure associated with the detonation of the explosive by acoustic filtering of the pressure wave. It is not intended that the mitigation system dissipate energy. In fact, it can be shown on theoretical grounds that, for this particular situation, energy dissipation in the compressible media is not of major significance (Reference 4). This is so because the explosive does work against the crush strength of the mitigation materials which is small compared to the transmitted pressures.

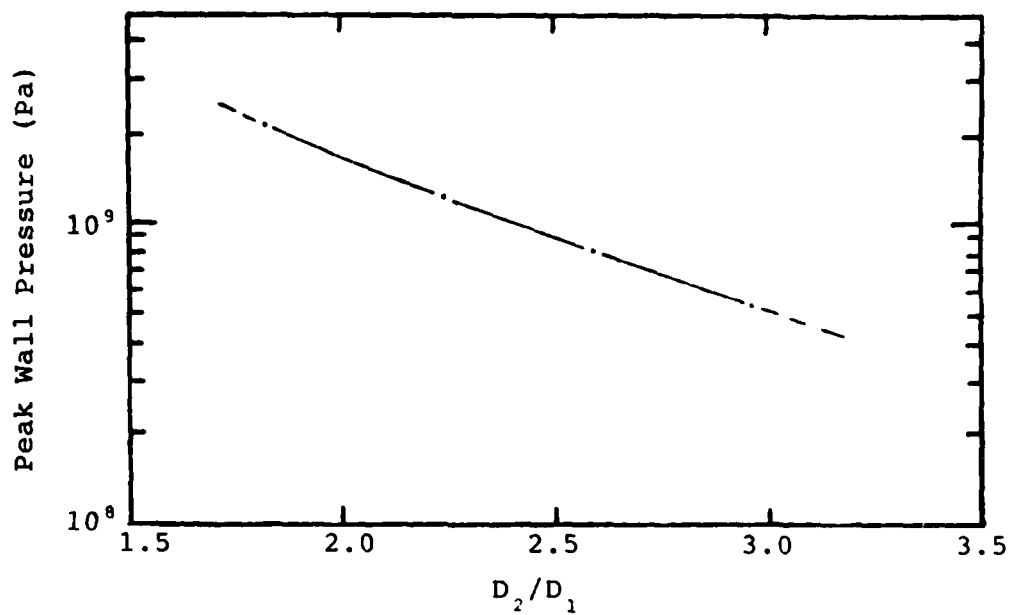
Several compact shock mitigation systems have been evaluated using STEALTH finite difference code calculations. These calculations modeled the detonation of the cartridge explosive, the passage of the stress waves through the several layers of alternating shock impedance and the propagation of the transmitted stress waves into the steel containment vessel.

We found that peak detonation pressures (350×10^8 Pa in Octol) can be attenuated by factors of 2 or 3 for mitigation systems where the combined thickness of the mitigation layers is approximately the same as the explosive thickness. This degree of attenuation was not felt to be sufficient to prevent severe damage to the steel containment vessel structure. The dispersion or spreading of the transmitted pressure pulse was less than expected primarily because of the non-linear material behavior at the high pressures involved. However, we believe this effort should be continued and supported by experiments.

3.2.2 Mitigation by Standoff Gap

In the second approach, a large standoff gap separates the outer layer of explosive from the inner wall of the containment vessel. The standoff gap allows the peak pressure to attenuate by geometric divergence.

Finite difference calculations were again used to size the gap so that the yield surface of the containment vessel would not be pierced by the initial pressure wave from the explosive detonation products. The variation of peak pressure on the inner wall versus standoff gap width is shown in Figure 9. The vessel wall thickness was sized so that long



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$D_1 \equiv$ Outside diameter of Explosive

$D_2 \equiv$ Inside diameter of Containment Vessel

Figure 9 Computed Peak Pressure on Inside Wall of Containment Vessel as a Function of Standoff Gap

term oscillations induced by the impulse loading of the detonation products did not exceed the yield surface (11.4×10^8 Pa material strength was assumed).

This is most likely a conservative approach since brief excursions through the yield surface of no more than a few microseconds can probably be tolerated. Typical calculated hoop stress histories in the containment vessel are shown in Figure 10.

3.2.3 Design Issues

The above calculations were used as a basis to design a first generation reusable containment vessel. The following design load conditions were evaluated:

1. Initial loading by detonation products
2. Subsequent long term vessel pressure oscillations
3. Equilibrium pressure
4. Impulse of explosive on vessel front end

The breech assembly design shown in Figure 11 represents a containment ratio of 250 (total weight of vessel to total weight of explosive). For use with a .0254 meter diameter plasma channel, the breech assembly would weigh 285 kg based on a preliminary plasma source design.

The standoff gap was specified based on the calculations discussed in Subsection 3.2.2. These calculations included the vessel response to the initial loading by the expanding detonation products as well as the long term wall stress oscillations resulting from this event. The standoff gap that is used to control the detonation shock transient also provides enough free volume to contain the dynamic pressures associated with expansion of the explosive products. A closed breech assembly such as shown in Figure 11 would have an equilibrium pressure of approximately 1.8×10^8 Pa (26,100 psi).

Calculation of the impulse imparted to the front end of the breech assembly is complex and was beyond the scope of this program. It was, however, evaluated experimentally and is discussed in Subsection 3.2.4.

The containment ratio of 250 is consistent with other explosive containment structures such as the Conical Shock Tube Blast Simulator Facility at the U.S. Naval Ordnance Laboratory (Reference 5) which also uses a standoff gap to attenuate the detonation shock. Containment ratios of 250 are representative for the surplus 16-in Naval gun barrels used to contain the charge.

We have projected that a containment ratio of 200 kg/kg is feasible and consistent with safety using high grade

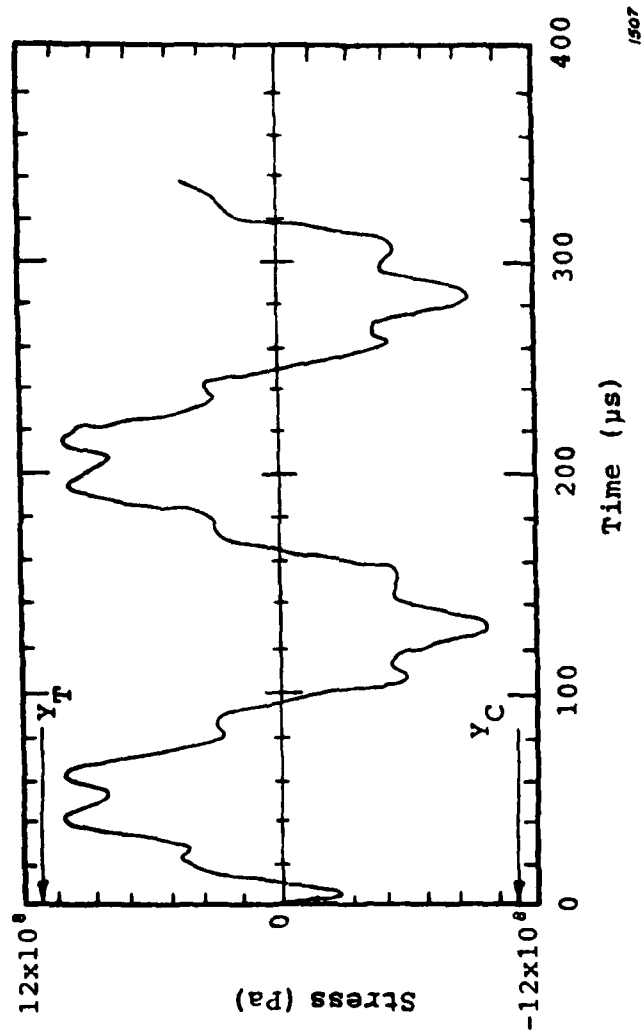
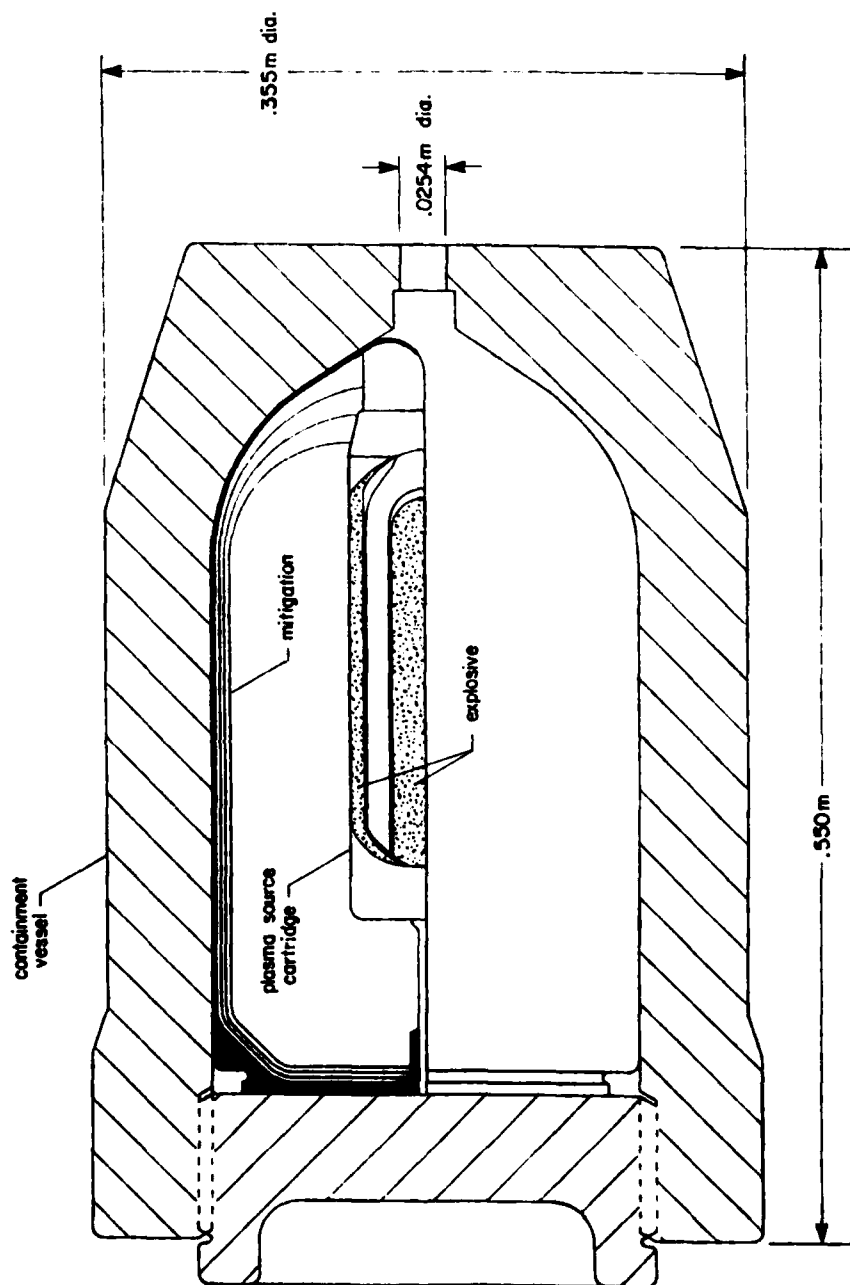


Figure 10 Computed Hoop Stress at Inner Wall of Containment Vessel



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steels. Lower containment ratios or higher safety factors would be possible with the use of specialty steels such as maraging steels or TRIP steels with high fracture toughness. Experimental demonstration of containment ratios 200 or less is one of the objectives of an in-house development program.

A large standoff gap may solve the containment problem for single shot applications but it is not necessarily the best solution for containment in a rep-rated device. A more compact shock mitigation scheme using a combination of gaps and shock attenuation/dispersal materials may be a method more compatible with rep-rating.

Artec has been involved in analytical and experimental work to develop lightweight blast containment structures in the past (Reference 4). One of the findings of this research was that fibrous absorber materials could be effective in attenuating peak dynamic pressures by converting a significant fraction of blast wave energy to thermal energy in the fibers during the initial expansion of the detonation products. This finding may have application in future cartridge designs.

3.2.4 Experimental

Artec undertook a small, internally funded program to experimentally evaluate the standoff gap mitigation approach to the impact of detonation products and to determine if other events are important in containment vessel design. A single shot reuseable containment vessel for PPMHD experiments was built (Figure 12) and preliminary tests were made. The ultimate objectives of this effort are to reduce testing costs and accelerate test turn around times by developing a reuseable PPMHD power supply assembly. These tests will also serve as sources of experimental data on cartridge containment using various containment strategies.

Several shots were fired in the vessel and there was no measureable vessel deformation. These tests were made with a layer of explosive formed around a wooden mandrel to provide the same explosive weight per unit length as the plasma source cartridge. The back end of the vessel was left open so this was a test of only the initial impulse loading of the vessel by the explosive detonation products.

Because of the direction of the detonation, the cartridge imparts substantial impulse to the front or downstream end of the breech assembly. The impulse, in turn, is transmitted into the generator structure. The effects of this impulse loading on both the breech assembly and generator structure have been evaluated experimentally and were not found to be serious for the test apparatus used.



Figure 12 Artec Reuseable Pulsed Plasma MHD Power Supply (Experimental)

3.3 MHD Channel Assembly

The plasma generated by the source flows down the channel and passes through a pair of electrodes positioned in the range of 8 to 40 diameters downstream of the channel inlet. The electrodes are not segmented and are mounted flush with the plasma channel walls.

In past experiments, an externally energized electromagnet field coil has been used to provide a reasonably constant transverse magnetic field of several teslas in the volume between the electrodes (Figure 13). The plasma velocity, applied magnetic field and resulting electric field are all mutually orthogonal. The current was conducted by a low inductance strip-line exiting through the field coil to an externally mounted load (Figure 13). Circuit inductances have been small (1 or 2 nanohenries) and plasma resistance was on the order of a few tenths of a milliohm. Load resistance was approximately matched to the resistance of the plasma. These channel assemblies were built for experimental use and were destroyed by the overpressures from the uncontained explosive plasma source cartridge.

3.3.1 MHD Channel Structure

The design of a reusable MHD channel must be a compromise between mechanical and electrical criteria. On the one hand, monolithic cylindrical containment structures are best suited for containment of mechanical loads such as the channel plasma and magnetic pressures. On the other hand, segmented structures are required to permit rapid diffusion of applied magnetic fields and to allow for the insulation necessary for voltage standoff. The magnetic field coil is wound tightly around the channel to minimize the required magnetic energy. The whole assembly must be integrated into a compact package to minimize energy losses and to control forces.

In recently completed designs, the MHD channel assembly includes a high-current transformer and power take-off in addition to the plasma flow channel, the electrodes and the magnetic field coil (Figure 14). Two parallel strip transmission lines connect the electrodes to the parallel transformer primaries. The high current transformer is located as close to the electrodes as possible to minimize resistive losses in the transmission lines and to localize the forces associated with the megampere currents.

The transformer secondaries may be connected in series or in parallel. There may be more than one electrode set. For example, in the method of self-excitation described in Subsection 3.3.4, an upstream MHD station provides the power for the field coil of a downstream MHD station.

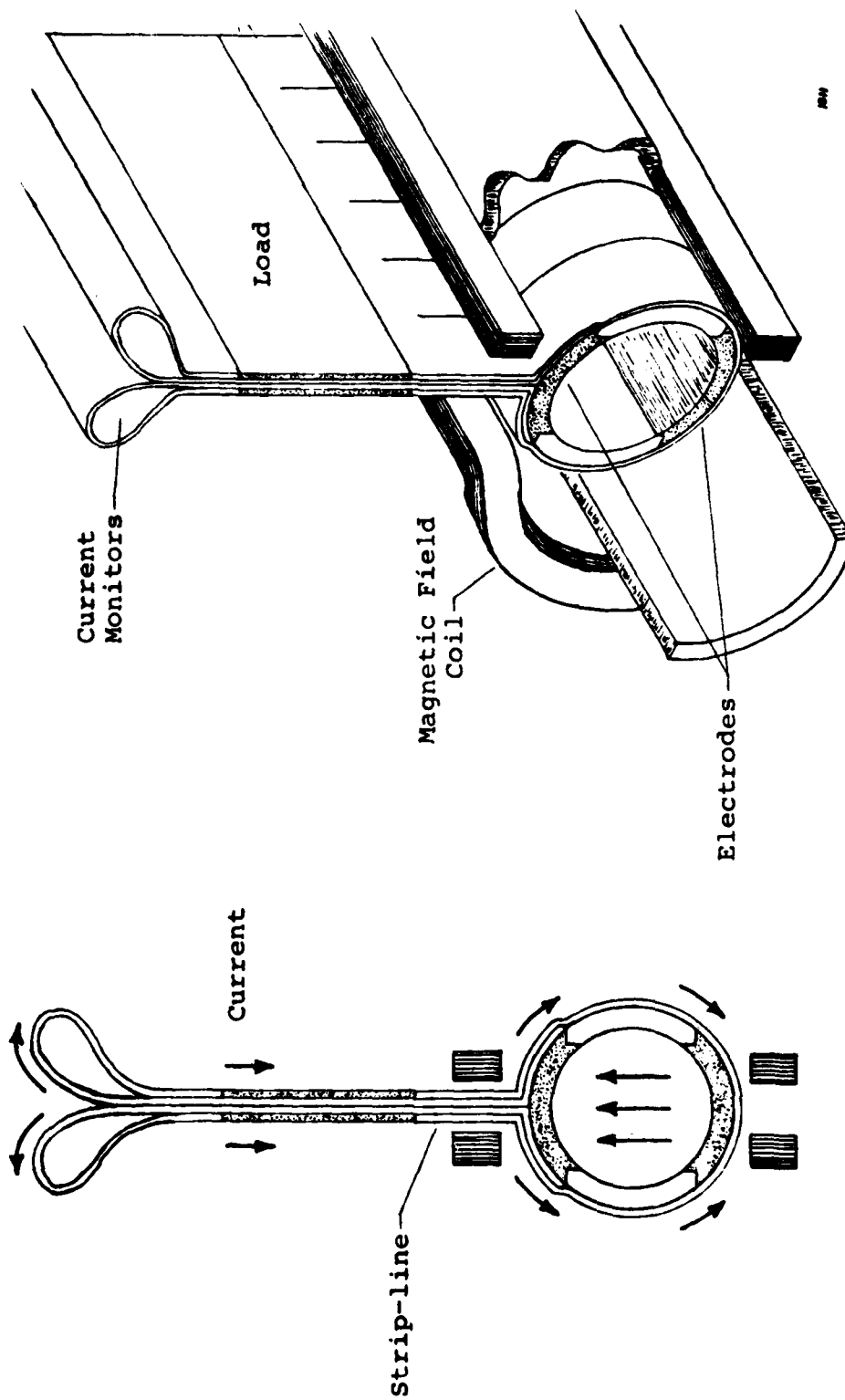
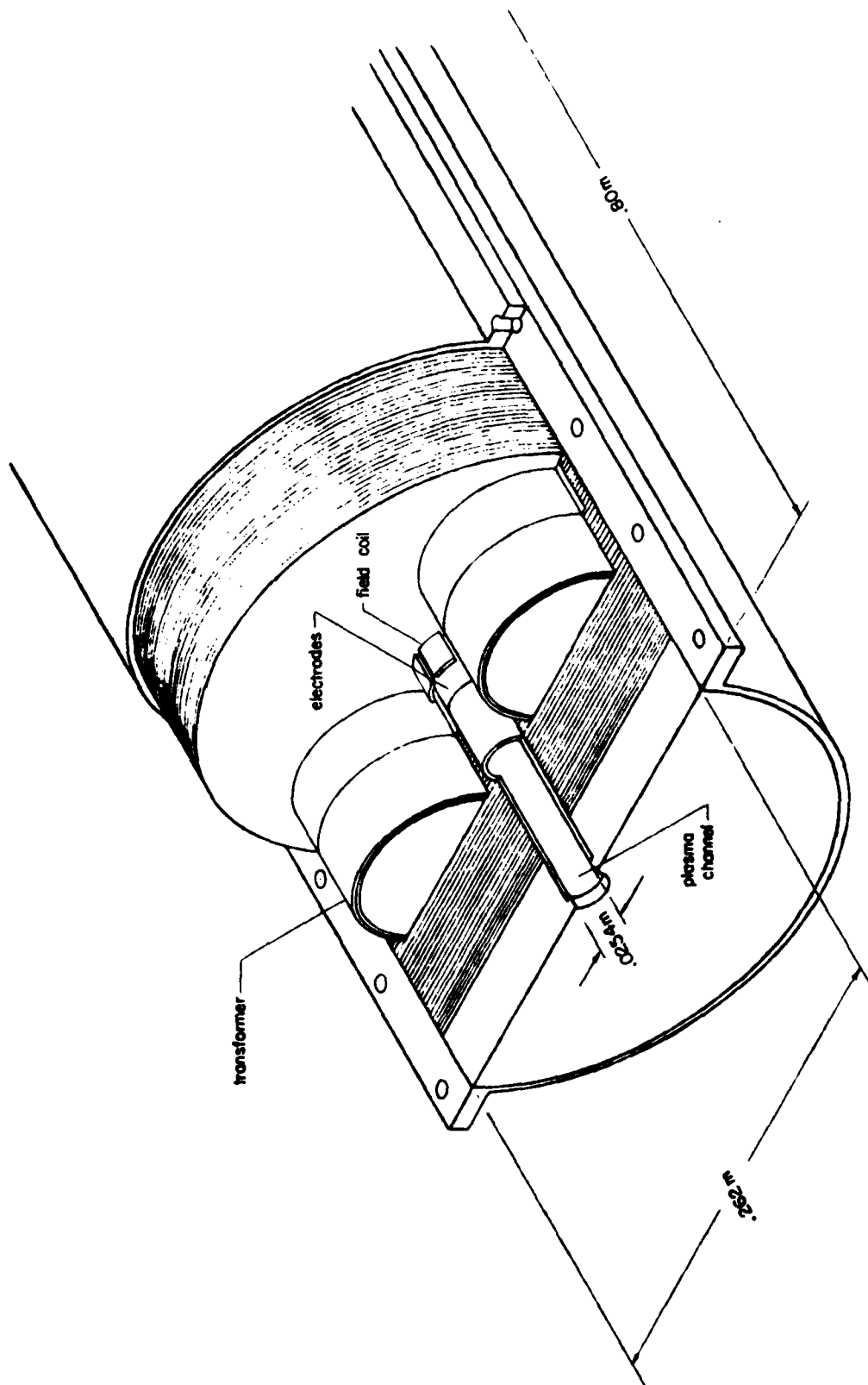


Figure 13 MHD Channel Assembly From Experiment 165-9



MHD CHANNEL ASSEMBLY		DATE	DESIGNED BY	APPROVED BY
ARTEC ASSOCIATES INCORPORATED				

The body of the structure is either cast from high strength insulating material or fabricated by stacking pre-cut plates which are electrically insulated to allow rapid buildup of the applied magnetic field. The plates may be made of steel, aluminum, high strength ceramics or resins.

The selection will be determined experimentally and is subject to four major considerations. The first is the ability to absorb the impulse from the plasma source cartridge which is transmitted through the cartridge containment vessel. The second consideration is the ability to contain the impulse from the electromagnet field coil. The third involves the forces in the transmission lines from the megampere currents during MHD power generation. These are applied asymmetrically and tend to split the channel assembly where the transmission lines pass through the field coil. The fourth is the ability to contain the hydrodynamic and magnetic pressures in the plasma channel.

Another key design area concerns the choice of plasma channel liner material and the manner in which the electrodes are mounted in the liner assembly. Erosion control and containment of pressures up to 3×10^6 Pa (3 kbar) are major considerations. The electrode sets typical of PPMHD are long and can severely weaken the channel liner structure. For rep-rated operation, plasma leakage around the electrodes can lead to serious accumulated damage.

The design of the MHD channel is complex and can best be handled empirically by utilizing an experimental test bed in which various materials and methods of fabrication can be evaluated.

A preliminary design of an MHD channel assembly based on a .0254 meter diameter plasma channel has been made under this contract. The design includes an integral field coil and two high current transformer structures in parallel. The body is composed of stacked aluminum plates. This design, shown in Figure 14, would weigh approximately 115 kg.

The electrical output energy of this design is estimated to be 120 kJ. The structure is designed to contain the combination of plasma and magnetic pressures developed in the channel, the forces from the pulsed electromagnet field coil and the magnetic stresses associated with the transformer. Peak pressures in the channel are no more than about 3×10^6 Pa based on detailed calculations of the MHD process. The peak magnetic energy developed in the field coil is approximately 17 kJ.

We have projected design improvements in the MHD channel assembly by the use of lightweight fiberglass plates and structural improvements. The projected weight of such an assembly is 60 kg. The electrical output energy of this size device resulting from projected improvements in the plasma source is 600 kJ. Peak channel pressures would rise to about 4×10^8 Pa. Pulsed field coil energy would be about 60 kJ.

For several applications the expended plasma must be controlled after passing through the MHD channel. This would be accomplished by bringing the plasma to rest in a plasma dump tank from which it can be vented in a controlled manner.

3.3.2 Field Coil

The applied magnetic field required by the PPMHD generator may be provided by a pulsed electromagnet. In recent experiments, we have used a saddle coil configuration driven by a capacitor bank. The peak field of several teslas is established in a few hundred microseconds and resistive losses in the coil have been on the order of 20% of the energy delivered to the coil.

In the MHD conversion process, the minimum required applied field volume is the volume between the electrodes. For example, a generator with a design output of 1 MJ (plasma channel diameter of .0508 meters) would typically require a .65 meter long electrode set (electrode volume of .0013 m³) and a 6 T field. The minimum applied magnetic energy is thus 19 kJ or 1.9% of the generator output energy.

The role of the field coil is to provide the required magnetic energy in the most efficient manner possible. In practice the magnetic field of the coil extends over a much larger volume than required. For example the saddle coil design used in the last PPMHD experiment (Reference 1) required over 12 times the minimum magnetic energy to establish the field between the electrodes. This design, however, was engineered for expediency not efficiency.

We have conducted a computational study of more efficient coil geometries. Key considerations were optimum distribution of coil elements, number of coil windings, resistive losses in the windings and compactness of coil windings around the plasma channel. As a result we found that a coil design could be fabricated that would require only 5 times the minimum magnetic energy. Further improvements in geometry can undoubtedly be made.

When the coil is energized by external means such as a capacitor bank resistive losses in the coil windings must be minimized. Resistive losses are usually on the order of 5% for a good design. For a self-excited coil design, skin effects must be considered because of the fast rise time required.

3.3.3 High-Current Transformer

An impedance transformer is built into the MHD channel assembly to transform down the large output currents and to control the resistive losses and magnetic forces associated with them. Because of the sizeable fields developed in the core, an air core design is the only practical choice. The transformer design shown in Figure 14 consists of two primary windings connected in parallel. This configuration reduces the magnetic forces by a factor of four compared to a single primary winding and distributes the forces more evenly in the channel assembly. The secondary windings of each primary are connected in series in this design.

One of the key considerations of this transformer design is the energy losses. We have evaluated several transformer designs to estimate these losses. When solid copper sheet conductors are used, the resistance in the transmission line and primary windings is controlled by skin depth criteria. The dominant energy loss mechanism is resistive losses in the transformer windings.

Several calculations were made to optimize rise time and to minimize droop and energy loss. These calculations assumed an MHD generator design with a .0254 meter diameter plasma channel. A .15 meter diameter primary was selected and an effective turns ratio of 6 was assumed, resulting in an output in the 30 kV range.

For a transformer of reasonable size with the required voltage standoff, transformer designs with 65% energy throughput were found to be feasible. It is apparent that substantial increases in transformer throughput efficiency can be achieved by reducing the resistance of both primary and secondary windings. We suggest that consideration be given to braided or segmented copper conductors to overcome skin depth limitations without seriously affecting the transformer coupling coefficient or characteristic droop. We project that transformer throughput efficiencies on the order of 80% will be achievable if these methods are successful.

3.3.4 Self-Excited Operation

As discussed in Subsection 3.3.2, we believe that an efficient field coil can be built. Designs have been evaluated for which the energy input to the coil is about 7% of

the energy output of the PPMHD generator. Alternately this can be expressed as an electrical energy amplification of 15.

One method of self-excitation is to drive the field coil of the MHD generator by the output of a small upstream MHD station. With this method the external electrical energy required to excite the upstream field coil is in effect amplified twice.

There are two potential problems associated with this approach. First the field coil of the main generator must be energized rapidly and reach peak current before the plasma passes through the electrode region. Second the energy losses through the field coil circuits must be minimized.

We investigated the possibilities of a practical configuration of self-excited operation employing the PPMHD simulation code described in Subsection 2.2 and Reference 1. A transformer was designed to match the output impedance of the upstream MHD generator to the field coil of the downstream (power) MHD generator. Based on the principles and analyses of Subsection 3.3.3, a six turn transformer with an energy throughput of 80% was assumed. A field coil for the downstream MHD generator was designed based on the analysis discussed in Subsection 3.3.2.

A number of computations were made to assess the sensitivity of self-excitation to sizing and location of the electrode stations.

The parameters representative of a practical arrangement are summarized below.

* Applied B-Field Upstream Generator	3.0 T
* Coil Energy Upstream Generator	2.5 kJ
* MHD Energy Out Upstream Generator	15.9 kJ
* Coil Energy Downstream Generator	12.7 kJ
* Max. B-Field Downstream Generator	5 T
* Load Energy Out Downstream Generator	88 kJ
* Overall Electrical Amplification	37.5

The results of these studies indicate that this approach to self-excitation is feasible and it should be straightforward to implement. The amplification or ratio of the downstream MHD generator output energy to the input energy of the upstream field coil was 37.5. That is, the required electrical energy input is only 2.8% of the PPMHD output. Energy losses through the upstream output circuit were dominated by resistive losses in the transformer. The peak B-field at the downstream MHD station was established by the arrival time of the plasma.

If this straightforward self-excitation scheme can be demonstrated experimentally, the implications for system weight in both single-shot and rep-rated systems will be substantial. Auxiliary power requirements will be minimal and the power supply for the applied field will be a small fraction of system weight.

4.0 REUSEABLE PPMHD POWER SUPPLY DESIGN

In this section, size scaling relations for PPMHD power supply components and assemblies are given. Two specific reusable power supply designs are discussed. These are:

1. A first generation test bed design with a .0254 meter diameter MHD plasma channel.
2. A large 5 MJ test bed design based on projected technology after considerable engineering development.

4.1 PPMHD Power Supply Scaling Relations

The weight of the PPMHD power supply can be estimated based on the component specific weight estimates established in Section 3.0.

The output pulse power, POW (GW), as a function of transformed output pulse energy, EMHD (kJ), is:

* Peak power, POW:

$$POW = K1 * (EMHD / EFFXF)^{2/3} * EFFXF \quad (1)$$

where $K1$ = function of plasma source technology and applied B-field
 $EFFXF$ = high-current transformer energy throughput efficiency

The weight of explosive, HEWT (kg), required in the cartridge can be expressed in terms of PPMHD output energy, EMHD (kJ):

* Explosive weight, HEWT:

$$HEWT = EMHD / (EFFXF * EFFMHD * 5300) \quad (2)$$

where $EFFXF$ = high-current transformer energy thruput efficiency
 $EFFMHD$ = MHD conversion efficiency (explosive to electrical)
 5300 = kJ/kg for Octol

Thus the component weights are:

- * Cartridge weight, CART:

$$CART = 1.5 * HEWT \quad (3)$$

- * Breech Assembly weight, BRCH:

$$BRCH = CR * HEWT \quad (4)$$

where CR = ratio of containment vessel
weight to explosive weight

The weight of the MHD channel, auxiliary power system
and plasma dump tank are estimated based on the PPMHD output
energy, EMHD (kJ), as:

- * MHD channel weight, CHAN:

$$CHAN = K2 * EMHD / EFFXF \quad (5)$$

- * Auxiliary power weight, AUX:

$$AUX = K3 * EMHD / (AMPL * EFFXF) \quad (6)$$

- * MHD channel diameter, DIA:

$$DIA = K4 * (EMHD / EFFXF)^{1/3} \quad (7)$$

where K2 = kg/kJ specific weight for
 the channel assembly based
 on PPMHD output energy
 K3 = kg/kJ specific weight for
 the auxiliary power supply
 based on energy output of
 the auxiliary power supply
 AMPL = electrical amplification
 for the B-field
 K4 = constant relating PPMHD
 output energy to channel
 diameter (depends on plasma
 velocity, plasma length,
 electrode length, B-field

Power supply weight, PS (kg), can be expressed as a sum
of component weights:

- * Power supply weight, PS:

$$PS = BRCH + CHAN + AUX \quad (8)$$

Estimates of autoloader and cartridge magazine weights
for rep-rated PPMHD power supply designs are given in
Reference 6.

The value of the constants based on current state-of-the-art performance levels are:

Current State-of-the-Art Technology

EFFMHD = .02 based on Shot 165-9 design
EFFXF = .65 based on achieved efficiency in lab tests
CR = 250 see Subsection 3.2
AMPF = 7 based on recent field coil designs
K1 = .16 from Shot 165-9
K2 = 1 kg/kJ see Subsection 3.3.1
K3 = 5 kg/kJ state-of-the-art capacitor technology
K4 = .00547 based on Shot 165-9 design

The projected value of the constants based on extensive engineering development are:

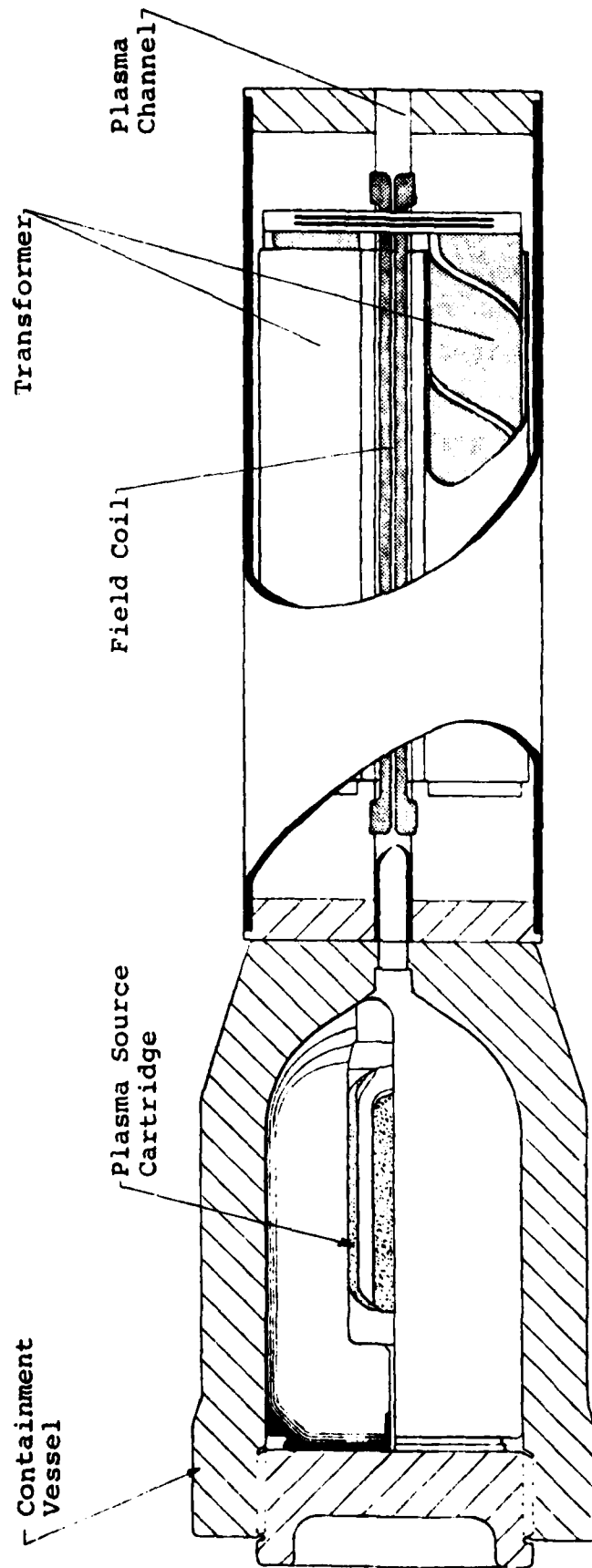
Projected Technology

EFFMHD = .12
EFFXF = .80 see Subsection 3.3.3
CR = 200 projected full containment
AMPF = 40 based on self-excited calculations
K1 = .23 based on improved plasma source and 7 T applied field
K2 = 0.1 kg/kJ see Subsection 3.3.1
K3 = 2.5 kg/kJ projected improvements in capacitor technology
K4 = .003

These represent optimum anticipated PPMHD component performance.

4.2 First Generation Reuseable PPMHD Test Bed Design

A reuseable PPMHD power supply design for an MHD channel diameter of .0254 meters is presented. The power supply includes an output impedance matching transformer. The component designs are based on established or readily demonstrated performance levels. A preliminary engineering drawing of the power supply is shown in Figure 15.



Breach Assembly

MHD Channel Assembly

REUSEABLE PPMHD POWER SUPPLY			
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Figure 15 Preliminary Design of a Reuseable PPMHD Power Supply

The specifications of this design, using relations (1) through (8) and current state-of-the-art values for the constants, are:

* pulse energy	65 kJ
* peak power	2.24 GW
* output volts (matched load)	30 kV
* Octol explosive weight	.94 kg
* cartridge weight	1.4 kg
* MHD channel diameter	.0254 m
* breech assembly weight	240 kg
* MHD channel assembly weight	100 kg
* auxiliary power supply weight	75 kg
* total PPMHD power supply weight	415 kg

This is the initial performance level of the reuseable PPMHD power supply that would be built for the test bed facility for the first year of the four year development program described in Section 5.0. As a result of component upgrade during the first year, output will be increased to 130 kJ at 3.9 GW. After four years of development, the projected output of the PPMHD test bed facility is 485 kJ at 13 GW and total power supply weight is projected to be under 300 kg.

4.3 Projected 5 Megajoule PPMHD Power Supply Test Bed

A reuseable PPMHD power supply design for a 5 megajoule electrical output is presented. Component weights are based on projected performance levels.

The specifications of this design, using relations (1) through (8) and projected values for the constants, are:

* pulse energy	5000 kJ
* peak power	62 GW
* output volts (matched load)	50 kV
* Octol explosive weight	9.8 kg
* cartridge weight	14.7 kg
* MHD channel diameter	0.1 m
* breech assembly weight	1960 kg
* MHD channel assembly weight	625 kg
* auxiliary power supply weight	390 kg
* total PPMHD power supply weight	2975 kg

This is the basic PPMHD power supply that could be built for a large 5 MJ EM launcher test facility. The technology needed to build a device of this overall efficiency would be available by the end of the four year development program described in Section 5.0. There are no inherent limits to developing even larger PPMHD power supplies to provide larger output pulse energies. An alternate approach would be to connect several PPMHD generators in series. This approach is feasible because of the extremely precise timing possible with these generators.

5.0 FOUR YEAR DEVELOPMENT PROGRAM

The following four year engineering development program is based on a small, reuseable PPMHD test bed that can be used to efficiently develop component designs and improve overall PPMHD efficiency and performance. At the end of the four years, we expect to be demonstrating a lightweight device with electrical output on the order of 500 kJ. The weight of explosive in the plasma source cartridge is less than 1 kg and the MHD channel diameter is .0254 meters. This is considered a reasonable size to conduct cost effective development work. The design is scaleable, with system weight approximately proportional to output electrical energy.

This program will address design issues relating to autoloader development and will include pertinent experiments of cartridge-mitigation system designs as a prerequisite for rep-rating the power supply. It is expected that other PPMHD development programs will be specifically aimed at developing PPMHD autoloader technology and hardware. The present program will provide technology support of these efforts.

The major year-end program goals are:

- Year 1. PPMHD reuseable test bed facility operational with some component development.
- Year 2. Extensive component upgrade and 7% overall energy conversion efficiency achieved.
- Year 3. Addition of self-excited operation and integral output impedance transformer. Energy conversion efficiency of 10% achieved.
- Year 4. Test bed operational with lightweight components. Extensive testing with various loads of interest. Energy conversion efficiency of 12% achieved.

The major program task areas for each year are presented in the following subsections.

5.1 Year 1 - Operational PPMHD Test Bed

Using established component technology, a first generation test bed facility will be fabricated and assembled. This will be based on the breech assembly and MHD channel assembly designs shown in Figure 15 and discussed in Subsection 4.2. The plasma channel diameter will be .0254 meters and the initial output pulse energy will be about 65 kJ at a

peak power of over 2 GW. The output pulse energy is assumed to be the output from an impedance matching transformer with a 65% throughput efficiency. Initially, the high current pulse transformer will be mounted externally on the MHD channel assembly to facilitate testing and maintenance.

The test bed will include comprehensive diagnostics to fully evaluate plasma source operation, MHD channel plasma conditions and electrical output voltages and currents. A description of these diagnostics is given in the Appendix. During the course of the program, the designs of many components such as the plasma source, electrodes and output transformer, must be assessed. The effectiveness of design improvements will be determined principally by the measured electrical output characteristics of the PPMHD power supply. We place considerable importance on the quality of the diagnostics and will use complementary techniques and redundancy where possible.

The PPMHD simulation code referred to in Subsection 2.2 and described in Reference 1, is an important tool in analyzing test results. In the past, we have used this code, calibrated to measured parameters, to determine system energy distributions and efficiencies and to help pinpoint performance variations in plasma conditions and in the electrical output circuits.

The breech assembly used in the first year will provide full containment of the plasma source cartridge and will be designed for an overall containment ratio of 250 kg steel per kg explosive. A major emphasis of the first year test bed program will be directed towards evaluation of MHD channel materials and fabrication techniques. Our goal is to develop a channel assembly that can withstand several shots with minimal component refurbishment using non-exotic materials but without particular regard for overall weight.

In this first year, we are planning to focus some effort on plasma source improvements since this is the area where the largest gains in overall energy conversion efficiency will be made. Design calculations referred to in Subsection 3.1 will be carried out and improved designs will be built and tested in the operational test bed apparatus. The test of design effectiveness will be increased electrical output power and pulse energy.

Concurrent with the development of the test bed apparatus, we will be conducting laboratory tests of compact field coil designs and will begin tests of high current impedance transformer designs. We will begin computational studies of self-excited MHD channel configurations such as described in Subsection 3.3.4. We will also investigate the latest developments in permanent magnet technology which hold the promise of a completely stand alone design without auxiliary electrical power requirements.

At the end of the first year, we will have established operational status of a fully diagnosed, reuseable PPMHD power supply test bed. Development of improved components (plasma source, pulse transformer, field coil) will be well underway. It is expected that overall energy conversion efficiency (explosive energy to delivered electrical energy) will be increased from the present level of 2% to over 4%. The anticipated power supply parameters at the end of Year 1 are:

* Test Bed Weight	460 kg
* Output Energy	130 kJ
* Loaded Output Voltage	30 kV
* Peak Output Power	3.9 GW

5.2 Year 2 - Component Upgrade

During the second year of the program, the emphasis will be on component upgrade and improvement of overall energy conversion efficiency.

Plasma source experiments will be continued with the goal of achieving most of the projected efficiency improvements and developing lower cost fabrication techniques. Some of these tests will be carried out at nearby explosive test sites to obtain flash radiographs of source operation. Most of the testing will be done in the reuseable test bed to measure improvements as evidenced by their effect on generator electrical output.

A second generation breech assembly will be developed based on the experiences of Year 1 and on a small scale test program. The design will incorporate a lightweight mitigation system. The expected overall containment ratio of this assembly is 200 (weight of assembly to weight of explosive in the cartridge). Studies will be initiated to evaluate the best approaches for rep-rated operation. These will include both revolver and reciprocating autoloader mechanisms. One of the objectives of these studies is to define the potential problem areas associated with round extraction.

One of the major goals of the Year 2 effort is the continued development of fabrication techniques and evaluation of materials for the MHD channel assembly. This includes new electrode mounting methods and plasma channel liners capable of withstanding many pulses without need of cleaning or refurbishment. Development of compact integral field coil designs and mounts along with lighter weight structures will be pursued.

Laboratory development of efficient air-core pulse transformers will be continued. Successful models will be evaluated on the reuseable test bed under design conditions of high current and energy throughput. These will not be intergral with the MHD channel assembly but will be mounted externally.

Self-excited computational studies will be continued during the second year. A modular MHD channel section containing an electrode/transformer subassembly will be fabricated. This will be inserted upstream of the main MHD power electrodes in the test bed apparatus for tests preparatory to full tests of self-excited operation. Output of both generator stations will be measured and the effect of the upstream power extraction on the plasma flow will be determined.

As a result of Year 2 work, a second generation design of the breech assembly and MHD channel assembly will be operational. The main structure of the breech assembly will be used for the remainder of the program with improvements to the internal mitigation system, breech closure and venting system added as necessary. Overall energy conversion efficiencies in excess of 7% will have been achieved primarily because of improvements in plasma source design. The PPMHD test bed apparatus will include a lightweight MHD channel incorporating an efficient field coil and long lasting plasma channel/electrode subassembly. The electrical output of the power supply, accounting for losses through the pulse transformer, is expected to be approximately 265 kJ. The anticipated power supply parameters at the end of Year 2 are:

* Test Bed Weight	430 kg
* Output Energy	265 kJ
* Loaded Output Voltage	40 kV
* Peak Output Power	7.3 GW

5.3 Year 3 - Self-Excited Operation

The objective of the third year program is to upgrade the test bed facility to include a third generation MHD channel assembly with integral impedance transformer and self-excited module. It is anticipated that the PPMHD power supply will achieve an overall energy conversion efficiency of 10%.

Continued development of the plasma source cartridge is expected to yield gains in overall efficiency. An efficient cartridge design will be established early in the third year to permit cost reduction in testing as a result of volume fabrication.

The second generation breech assembly, developed during Year 2, will be used with improvements being added as warranted. These will include improved mitigation systems and features to assist with round extraction experiments. The continuing design effort to develop an autoloading technology will be complemented by experiments in the test bed facility.

A third generation, lightweight MHD channel assembly will be designed and built. This will include an integral output impedance transformer for the main power generator and a self-excited module. The self-excited module, which is added to the channel assembly upstream of the main power electrodes, will be comprised of an electrode set subassembly and impedance matching transformer to provide the necessary output voltage to drive the field coil of the main power electrodes.

The test bed facility will be capable of 365 kJ output at 10 GW power levels. The PPMHD power supply, consisting of a second generation breech assembly and third generation MHD channel assembly will weigh on the order of 330 kg. It will require about 10 kJ of auxiliary electrical energy to establish the magnetic field required by the self-excited MHD electrodes. The anticipated power supply parameters at the end of Year 3 are:

* Test Bed Weight	330 kg
* Output Energy	365 kJ
* Loaded Output Voltage	45 kV
* Peak Output Power	10 GW

5.4 Year 4 - Benchmark Testing

The fourth year will emphasize extensive testing under various load conditions. With improvements in plasma source design and self-excited operation, overall energy conversion efficiencies approaching 12% should be realized.

Some development work will be carried out to improve the plasma source cartridge and shock mitigation system in preparation for advanced autoloader experiments. It is expected that this effort will be part of a larger program to develop a lightweight autoloader system for a PPMHD power supply. The breech assembly developed in the second year of the program will continue to be used.

Most of the fourth year program will be aimed at testing the power supply under various output load conditions. This could include, for example, charging a large storage inductor using a second high voltage transformer. This would be applicable to EM launcher technology. Experi-

ments in which pulse forming networks (PFN's) are energized by the PPMHD power supply would also be candidates.

The anticipated power supply parameters at the end of Year 4 are:

* Test Bed Weight	290 kg
* Output Energy	485 kJ
* Loaded Output Voltage	50 kV
* Peak Output Power	13 GW

5.5 Program Schedule, Milestones and ROM Costs

The schedule for technical tasks for the four year development program is shown in Figure 16. The tasks are subdivided into design, experimental, fabrication and refurbishment categories. "Design" includes all engineering design and analysis functions. "Experimental" pertains to laboratory or test site experimental work other than that carried out in the test bed facility. "Fabrication" includes all fabrication of hardware for the test bed apparatus or test bed development tests. "Refurbishment" includes test bed maintenance, resupply. Testing activities in the PPMHD test bed facility are treated separately as "System Tests".

The major program milestones, also shown in Figure 16, are as follows:

Year 1

1. Begin system tests (end of month 7)
2. First generation improved plasma source available (end of month 9)
3. Test bed operational with 130 kJ output at 30 kV (end of month 11)

Year 2

4. Second generation breech assembly installed (end of month 6)
5. Second generation lightweight MHD channel assembly installed (end of month 6)
6. Operational pulse transformer developed (end of month 8)
7. 265 kJ output (mid month 10)

Year 3

8. Third generation MHD channel assembly installed (end of month 5)
9. Self-excited module operational (end of month 7)
10. 365 kJ output (end of month 11)

Year 4

11. Benchmark testing begun (start of month 4)
12. 485 kJ output (end of month 6)
13. Fully operational PPMHD test bed (end of month 9)

The rough-order-of-magnitude costs for each of the four years are given below. These are not adjusted for inflation.

Year 1	Plasma Source	175
	Breech Assembly	225
	MHD Channel Assembly	220
	System Tests	240
	Management	60
	Total	920
Year 2	Plasma Source	200
	Breech Assembly	300
	MHD Channel Assembly	300
	System Tests	200
	Management	75
	Total	1075
Year 3	Plasma Source	225
	Breech Assembly	125
	MHD Channel Assembly	350
	System Tests	275
	Management	75
	Total	1050
Year 4	Plasma Source	175
	Breech Assembly	125
	MHD Channel Assembly	200
	System Tests	400
	Management	100
	Total	1000

YEAR 1

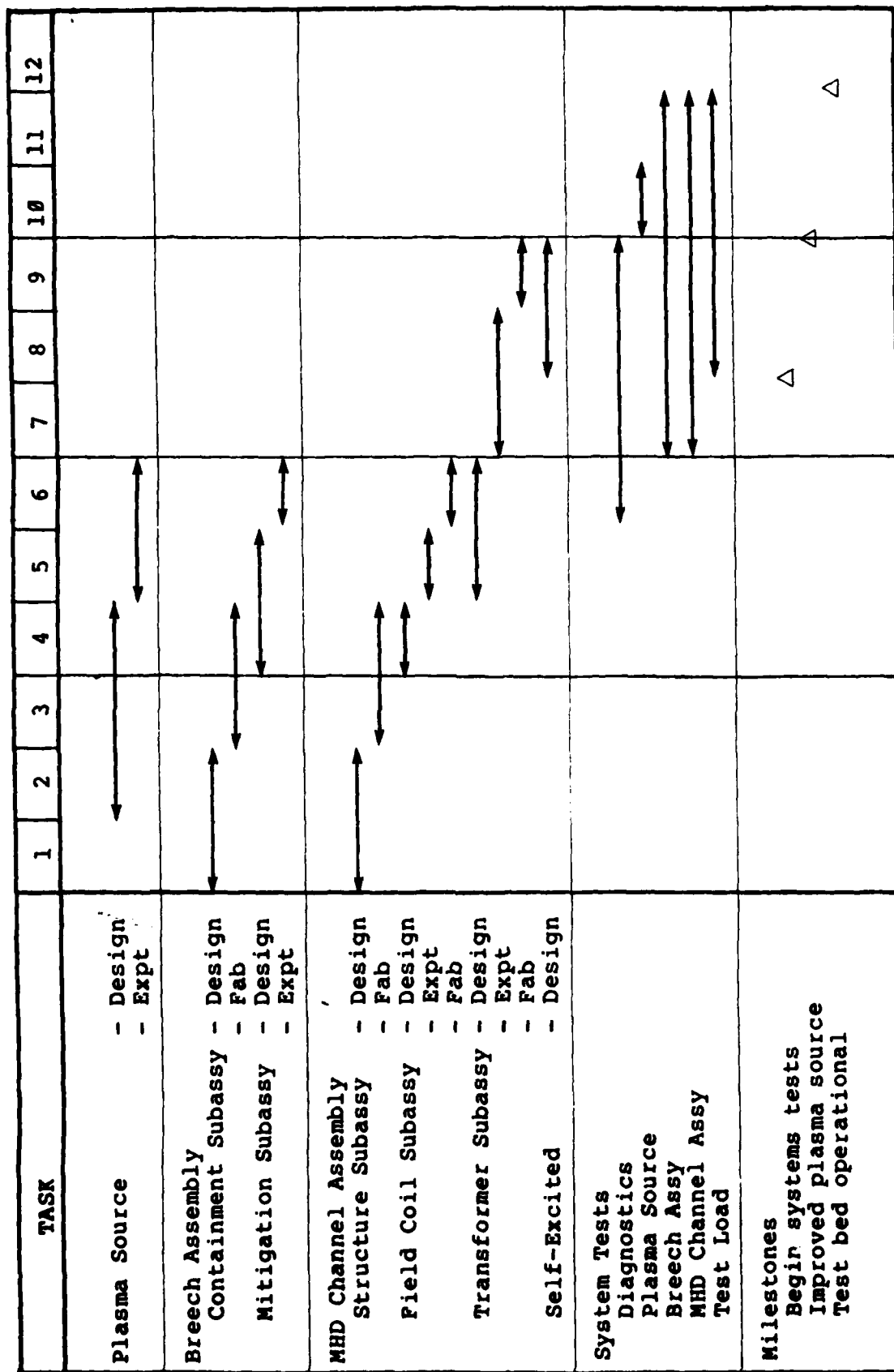


Figure 16 Program Schedule

YEAR 2

TASK	1	2	3	4	5	6	7	8	9	10	11	12
Plasma Source - Design - Expt		↔	↔		↔							
Breach Assembly Containment Subassy - Design - Expt - Fab Mitigation Subassy - Design - Fab Autoloader Issues - Design	↔	↔	↔	↔	↔		↔					
MHD Channel Assembly Structure Subassy - Design - Fab Field Coil Subassy - Design - Expt Transformer Subassy - Design - Expt - Fab Self-Excited - Design - Fab	↔	↔	↔	↔	↔	↔	↔	↔	↔			
System Tests Plasma Source Breach Assy MHD Channel Assy Test Load							↔	↔	↔	↔	↔	
Milestones 2nd breach installed 2nd MHD channel installed Operational pulse xformer 265 kJ output						△	△	△				

Figure 16 (con't)

YEAR 3

TASK	1	2	3	4	5	6	7	8	9	10	11	12
Plasma Source	- Design - Fab	↔	↔	↔								
Breach Assembly												
Containment Subassy	↔		↔		↔	↔						
Mitigation Subassy												
Cartridge Extract				↔	↔	↔	↔					
MHD Channel Assembly												
Structure Subassy	- Design - Fab	↔	↔									
Field Coil Subassy	- Design - Fab	↔	↔									
Transformer Subassy	- Design - Fab	↔	↔									
Self-Excited	- Design - Fab	↔	↔									
System Tests												
Plasma Source												
MHD Channel Assy												
Test Load												
Milestones												
3rd MHD channel installed												
Self-excited operational												
365 kJ output												

Figure 16 (con't)

YEAR 4

TASK	1	2	3	4	5	6	7	8	9	10	11	12
Plasma Source		↔	↔	↔								
Breech Assembly												
Containment Subassy		↔	↔									
Mitigation Subassy		↔	↔									
Cartridge Extract			↔	↔								
MHD Channel Assembly												
Structure Subassy		↔										
Field Coil Subassy		↔										
Transformer Subassy		↔										
Self-Excited		↔										
System Tests												
Plasma Source							↔	↔				
Loads of Interest							↔	↔				
Milestones												
Start benchmark testing												
485 kJ output												
Test bed fully operational												

Figure 16 (con't)

6.0 CONCLUSIONS

Design procedures have been developed for estimating component weights for a reuseable PPMHD power supply. Based on these procedures, a preliminary design of a power supply test bed apparatus has been made. This will serve as a facility for PPMHD component development and upgrade. Initially, the power supply, weighing about 415 kg, will be capable of a 65 kJ output pulse at 2 GW. After four years of component development and upgrade, the output will be nearly 500 kJ at an average power level of 10 GW. The power supply, which includes full containment of the explosive cartridge, self-excited generator operation, auxiliary power supply and output impedance transformer, is projected to weigh less than 300 kg.

The design will include provision for autoloader equipment and will be upgradeable for rep-rating. The basic design is size scaleable and PPMHD power supply units with 5 MJ or larger output pulse energies are feasible.

A four year program is outlined to upgrade the PPMHD test bed facility and demonstrate operation with pulse conditioning equipment and energy conversion devices of interest. PPMHD power technology is unique and is considered one of the very few viable power supply options for several directed energy applications requiring lightweight, rep-rated pulse power. It is in the national interest to maintain a PPMHD facility in place to respond quickly to the needs of the various directed energy and kinetic energy weapons programs.

For single pulse applications, extremely lightweight PPMHD power supplies are possible since explosive containment structures are not required and lightweight, inertially confined MHD channel assemblies are possible. Single shot lightweight power supplies with electrical output energies of several megajoules are feasible using a flux compression device with a small PPMHD generator to provide the priming flux.

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APPENDIX

PPMHD DIAGNOSTICS

PARAMETER: Magnetic Field.

Typically 2 to 8 tesla during operation. Generated by a saddle coil electromagnet. B-field versus time is recorded.

PURPOSE:

This field is used to calculate the MHD interaction in the channel. Generated voltage is proportional to this field and the electrical power output is proportional to the magnitude of the field squared. Hence accurate field information is necessary to compare theoretical and actual performance.

MEASUREMENT TECHNIQUE:

- a. The voltage integral of a pick up coil wound inside the electromagnet is measured using an R-C filter and an oscilloscope.
- b. A Rogowski pick-up coil which is designed to fit over the electromagnet lead connection is used to monitor the magnet current versus time.

The directly encountered voltage levels and the signal conditioned voltage levels are:

	<u>DIRECT</u>	<u>CONDITIONED</u>
a.	270 V	12 V
b.	2.5 V	.10V

PPMHD DIAGNOSTICS

PARAMETER: Diaphragm Opening Time

Triggered by intense emission from the 30,000 K plasma when the diaphragm separating the plasma source from the MHD channel is burst open.

PURPOSE:

This is an indicator of normal plasma source operation. Diaphragm opening time is usually reproducible, from shot to shot, within a microsecond. Diaphragm opening time is also used as the first time-of-arrival point of the plasma shock trajectory in the MHD channel.

MEASUREMENT TECHNIQUE:

Battery powered photodiode mounted at the downstream end of the MHD channel responds to intense emissions from the plasma.

PPMHD DIAGNOSTICS

PARAMETER: Time-of-Arrival of Detonation Front.

Responds to the thin conductivity zone in the detonation wave of the plasma source explosive.

PURPOSE:

Gives the velocity of the detonation front. Monitors performance of the explosive. Shot to shot variation is submicrosecond so this data confirms normal operation of the plasma source.

MEASUREMENT TECHNIQUE:

Uses a sequence of shorting pins in direct contact with the explosive. Output is recorded on a raster oscilloscope. Shorting pins are made from a miniature coaxial cable (Microdot cable) having a solid outer conductor. The submillimeter detonation zone of the explosive is conductive and completes a circuit, dumping a small capacitor.

PPMHD DIAGNOSTICS

PARAMETER: Plasma Velocity.

10 to 30 km/sec. Open circuit Faraday generator gives a voltage of 60 volts with a B-field of 0.1 tesla and electrode separation of 3 cm. Velocity versus time is recorded.

PURPOSE:

Correlate with other parameters; used to estimate kinetic energy of plasma as well as the change in kinetic energy from electrode inlet to electrode outlet when measurements are made outside both ends of the active conversion volume. Used in interpreting matching computer calculations using the full PPMHD simulation code. Used to verify cartridge performance. Used as time-of-arrival data for MHD channel plasma shock trajectory. Used to monitor generator flow interaction. Useful for modeling generator performance as it is directly proportional to generator open circuit voltage.

MEASUREMENT TECHNIQUE:

Uses open circuited MHD generators with small permanent magnet to provide the B-field. Velocity is directly proportional to open circuit voltage ($u = v_{oc} / Bb$). Sometimes the main B-field is used, with probes on the saddle coil axis. The usual voltage range for these measurements is 35-110 volts directly from the open circuited generator terminals and about 15 volts conditioned to an oscilloscope.

PPMHD DIAGNOSTICS

PARAMETER: Plasma Conductivity.

10-30 kilosiemens/meter (in the range of electrical conductivity of graphite).

PURPOSE:

Correlate with generator performance parameters. Used to assess the effectiveness of energy transfer to the argon gas. Used as time-of-arrival data for MHD channel plasma shock trajectory. Used to calculate inter-electrode plasma resistance which is one of the elements in the electrical circuit. Used in interpreting matching computer calculations using the full PPMHD simulation code. Used in conjunction with conductivity theory to verify plasma state.

MEASUREMENT TECHNIQUE:

- a. From the generator current history, open circuit voltage history and the external circuit parameters, calculate the internal resistance and infer the average plasma conductivity assuming that conducting path fringing is negligible.
- b. Choosing a place along the channel where dB/dz exists (magnet leading or trailing end), locate a pick-up coil outside the channel wall. As the plasma flows through the region of the spatially varying magnetic field, an eddy current, is generated in the plasma. The magnetic field of this eddy current couples into the pick-up coil. The integral of the pick-up coil induced voltage is proportional to the magnetic Reynolds number of the plasma, and this in turn is related to the conductivity-velocity product. Calibration is carried out in the lab by launching an aluminum bar down a channel with the same magnet configuration and channel size. The velocity of the bar is measured, the conductivity of aluminum is known, the magnetic Reynolds number is calculated, and the output versus magnetic Reynolds number is determined. The range of Re_m is 5-30.

PPMHD DIAGNOSTICS

PARAMETER: Generator Voltage.

1-3 kV range, using direct connections at various locations along the output transmission strip lines connected to the electrodes. Voltage versus time is recorded.

PURPOSE:

The generator voltage is used in the integral of the voltage-current product to assess the electrical energy delivered by the MHD device. It is also used in correlating the plasma properties ($v = B_{ub} - I_b / A - L dI/dt$) with the channel parameters. Used as time-of-arrival data for MHD channel plasma shock trajectory

MEASUREMENT TECHNIQUE:

Direct measurement using a resistive voltage divider. Voltage versus time is recorded on an oscilloscope; sweep is initiated via a delayed trigger referenced to the detonation initiation pulse. The directly encountered voltage levels and the signal conditioned voltage levels are:

DIRECT

1-4 kV

CONDITIONED

15 V

PPMHD DIAGNOSTICS

PARAMETER: Generator Current.

1-5 Megampere range.

PURPOSE:

The generator current is used in the integral of the voltage-current product to assess the electrical energy delivered by the MHD device. It is also used in correlating the plasma properties (along with the voltage and magnetic field) and channel parameters. Used as time-of-arrival data for MHD channel plasma shock trajectory.

MEASUREMENT TECHNIQUE:

The current measurement is usually accomplished using an inductively coupled probe. This is generally a 3-10 turn pick-up coil which is mutually coupled to the device output stripline. The load current produces a magnetic field, the time varying field induces a voltage in the pick-up coil, and the integral of this voltage is proportional to the load current (current is proportional to the magnetic flux in the coil which is proportional to dB/dz). The current versus time is displayed on an oscilloscope. Probe calibration is effected by providing a known $I(t) = I_0 \sin \omega t$ to generator output circuit and calibrating the coil integrator measurement circuit.

PPMHD DIAGNOSTICS

PARAMETER: Plasma Pressure History.

0.1 to 5×10^8 Pa (.1 to 5 kilobars)

PURPOSE:

Pressure histories along the MHD channel provide additional data for matching calculations of channel flow using the PPMHD simulation code. Pressure histories and electrical conductivity histories can be used in conjunction with conductivity theory to estimate plasma internal energy or density. Important also for designing MHD channel structure.

MEASUREMENT TECHNIQUE:

Commercial piezometric gages have been used with limited success because of electromagnetic transients. Bar gages have been used also with limited success.

PPMHD DIAGNOSTICS

PARAMETER: Energy Absorbed by Load.

30-2000 kilojoules in a resistive load.

PURPOSE:

Calorimetric determination of the energy supplied to a load from the MHD device provides an independent verification of the overall performance of the PPMHD generator.

MEASUREMENT TECHNIQUE:

- a. Determine the individual masses of the load and of the energy absorbing liquid in which the load is immersed, these being placed in a thermally insulated container. Determine the average temperature change of the masses due to the energy deposited by the MHD output pulse. Using the known masses, specific heats, and temperature change, compute the energy absorbed by the calorimeter components.
- b. Thermocouple attached to the load and appropriately insulated, calibrated in the lab by discharging a capacitor bank through a known load.
- c. Temperature indicating laqueurs calibrated by a capacitor bank and known load.

PPMHD DIAGNOSTICS

PARAMETER: Flash X-rays of Plasma Source Cartridge.

PURPOSE:

120 MEV flash X-rays of the cartridge taken during detonation are used to view the plasma generation process employed in this concept. The X-rays provide a corroboration of the radial compression of the annular gas volume as well as a snapshot of the axial progression of the process.

MEASUREMENT TECHNIQUE:

Use the 120 MEV LINAC flash X-ray capability of the Lawrence Livermore Laboratory Test Site.